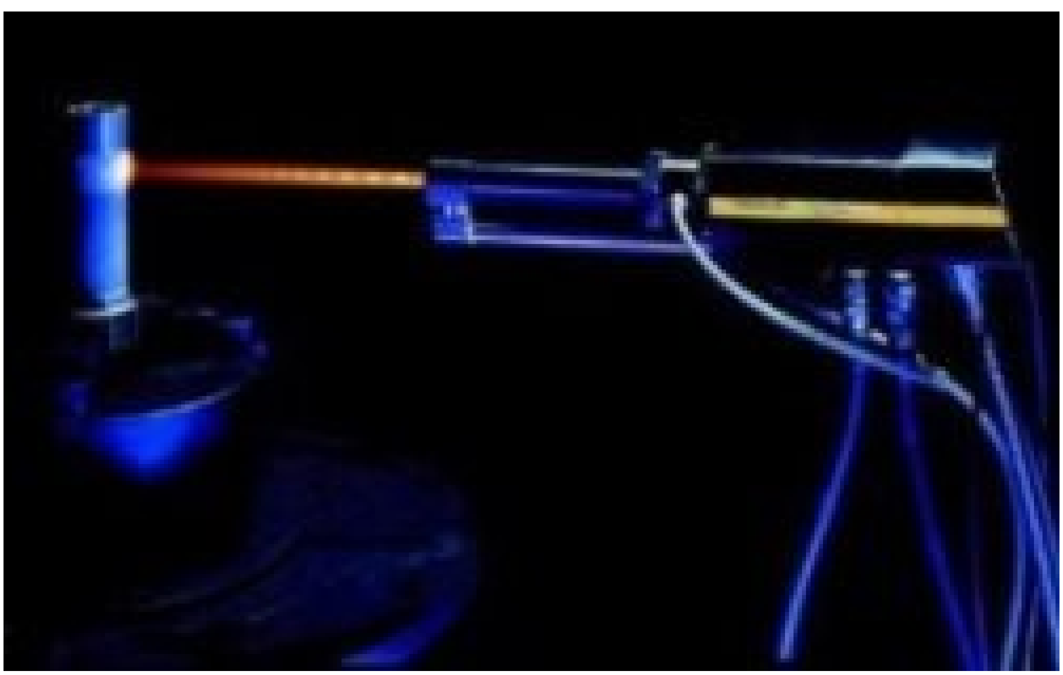
THERMAL SPRAYING TRAINING MODULE: FOR AS-SPRAYED (UN-POLISHED) COATINGS

André McDonald, P.Eng.
Assistant Professor
Dept. of Mechanical Engineering
University of Alberta

Kelly Schoof, P.Eng.
Manager
Western Hard-Chrome Plating, Ltd.

Bernard Harvey
Technical Officer, Surface Technologies
Industrial Materials Institute (IMI)
National Research Council Canada (NRC)



I The Thermal Spraying Process – A Brief Overview

Thermal spraying is a process in which a high-temperature heat source is used to melt and accelerate micron-sized metal, ceramic, or alloy particles to build thick protective coatings on industrial machine component substrates. Molten and semi-molten particles impact and spread on the component surfaces until several layers of the coating are fabricated. These coatings provide protection against degradation caused by corrosion, erosion, or high temperatures. The versatility and cost-efficiency of thermal-sprayed coatings have increased their use in diverse industrial applications in aeronautics, automotives, biomedical, mining, and petroleum.

Thermal spray coating deposition involves the use of a torch to heat a material (**Fig**. 1), in powder or wire form, to a molten or near-molten state, and the use of a gas to propel the material to the target substrate, creating a completely new surface. The coating material may be a single element, alloy or compound with unique physical properties that are, in most cases, achievable only through the thermal spray process.

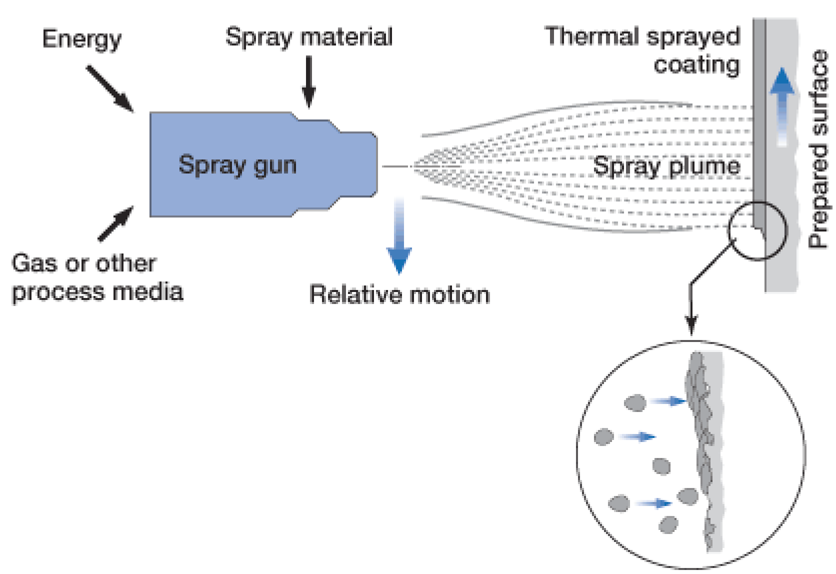


Figure 1 The thermal spraying process (www.sulzermetco.com)

New developments in thermal spraying have resulted in a new process known as cold-gas dynamic spraying ("cold spraying"). Cold spraying is a process of applying a coating layer by depositing fine, micron-sized particles at high speeds (100 to 1200 m/s) onto metallic substrates (**Fig**. 2). The high impact speeds of the particles promote rapid spreading, plastic deformation, and the deposition of a highly dense layer of particles. Bonding between the deposited particles is typically metallurgical, coupled with mechanical interlocking. The absence of high temperature particle heating during the deposition process eliminates oxidation, promotes retention of the properties of the original stock powder, induces low residual stresses in the coating, permits the deposition of thermally sensitive materials such as polymers, and facilitates the deposition of highly dissimilar materials.

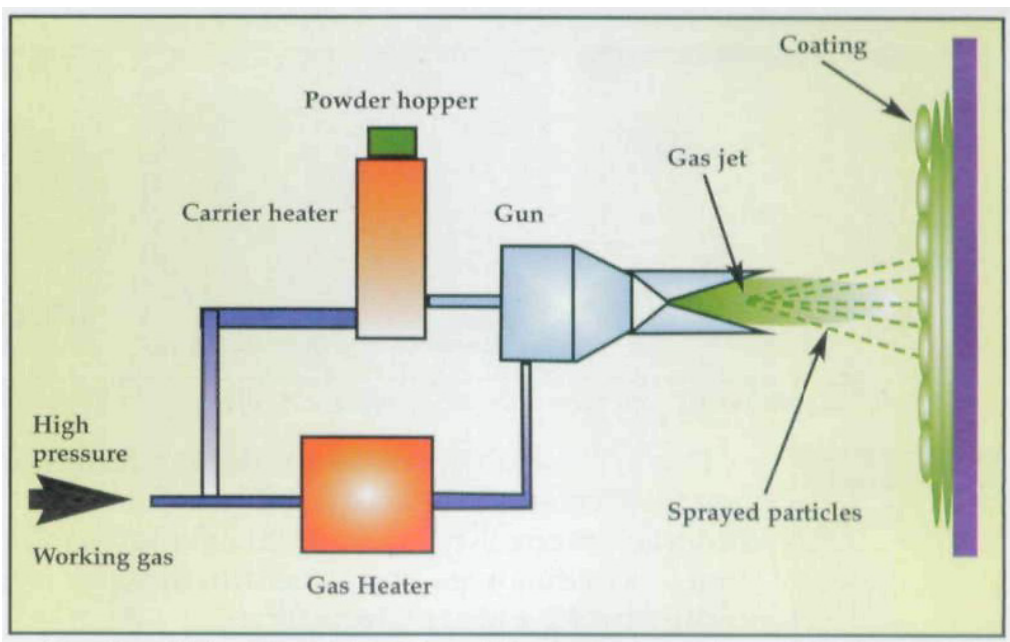


Figure 2 The cold spraying process (J. Karthikeyan, Adv. Mat. Proc., March 2005, 33)

II The Coating Deposition Process - Training

The following general steps are required for the deposition of high-quality coatings. These steps may be modified to fabricate more specialized coatings.

1 Powder Sieving and Preparation

Powders can be sieved to narrow size distributions, as appropriate. A Ro-Tap siever, complete with sievers can be used. The siever shakes and taps the powders in the sieves, segregating the particles in the appropriate sieves. Available sieves are:

Sieve Size #	**Conversion**	
	microns	**inch**
635	20	0.008
400	38	0.015
325	45	0.017
270	53	0.021
230	63	0.025
170	90	0.035

Reporting of powder size distribution follows an established format. For example, a sample of powder that contains particle sizes ranging from 38 to 63 microns would be reported as **-63+38 µm**.

The sieves must be cleaned after each use. This will prevent unwanted mixture of different powders and blockage of the sieves due to moist powder. An ultrasonic test sieve cleaner is used to clean the sieves. The sieves are placed in a water bath in the cleaner. Ultrasonic vibrations will loosen the powder particles from the sieve. It is recommended to clean one sieve at a time, though multiple sieves may be cleaned at each instant. After ultrasonic cleaning, the sieves are dried with blasts of dry, compressed air.

2 Substrate Preparation: Grit Blasting

Grit blasting is a process in which the substrate surface is hit repeatedly by a large number of abrasive pellet particles. These particles remove surface oxides and contaminants. The surface is also roughened to promote increased adhesion of the deposited coating. The pellet grit material may be sand, glass beads, iron, silicon carbide, or aluminum oxide, to name a few. For the thermal spraying process, aluminum oxide grit is typically used.

Grit blasting is typically done in a closed chamber. The grit pellet particles are projected at high speed through a nozzle to impact on the substrate. The chamber is equipped with a valve that is opened with the foot to permit discharge of the particles through the nozzle. In some cases, the particles are collected and reused. **Figure** 3 shows a picture of a typical grit blasting chamber. As shown, the chamber comes equipped with hand gloves in the front of the chamber.

Figure 3 A typical grit blasting chamber

Grit sizes vary, and use of a specific size will depend on the required final roughness of the substrate. Smaller grit sizes indicate larger sizes of the grit material. Larger grit pellets will roughen the surface to a greater extent and within a shorter period of time. **Table** 1 shows typical grit size numbers and the average approximate sizes in inches and microns.

Grit Size #	Conversion	
	inch	**microns**
8	0.087	2210
10	0.073	1854
12	0.063	1600
14	0.053	1346
16	0.043	1092
20	0.037	940
24	0.027	686
30	0.022	559
36	0.019	483
46	0.014	356
54	0.012	305
60	0.010	254
70	0.008	203
80	0.0065	165
90	0.0057	145
100	0.0048	122
120	0.0040	102
150	0.0035	89

Table 1 Grit size conversion chart

i Grit Blasting Procedures

The following are some general operating procedures to grit blast a surface.

a) Cover those areas of the substrate that will not be grit blasted with electrical or aluminum tape.

b) Place the substrate in the chamber, and turn the chamber lights ON. Ensure that the chamber door is securely closed before grit blasting the substrate.

c) Turn ON the compressed air system and allow the blast pressure to build before blasting the surface. This will allow the entire substrate sample to have a uniform roughened surface.

d) Hold the substrate sample firmly in front of the discharge nozzle. Samples held close to the nozzle exit will have rougher surfaces.

e) Open the valve (or press pedal) to permit discharge of the grit pellets through the nozzle.

f) To ensure uniform roughness, pass the nozzle over the surface at constant speed. Multiple passes may be needed to ensure that the desired roughness is achieved.

g) It is highly recommended to follow a "left-right" or "top-bottom" pass sequence of the nozzle during the blasting process. Typically, only one pass is needed to roughen the entire surface. Constantly passing the nozzle over the surface will result in work hardening and rough profile deterioration.

h) When satisfied with the level of surface roughness, turn OFF the compressed air system, and remove the roughened sample. **Note**: Do not close the grit valve when the substrate is at the nozzle exit. Complete the grit blasting, aim the nozzle away from the sample, and close the valve (pedal). For recycling systems, check the collected grit for evidence of fragmentation. Broken or pulverized grits will reduce the quality of the blasting process.

i) Ensure that the chamber door is closed and all the lights are OFF after completing the grit blasting procedures.

j) Visually inspect the surface to ensure that there are no "shiny" areas, and that the surface is uniformly roughened.

k) Use a surface profilometer to measure the average roughness (R_a) of the surface.

3 Substrate Thickness Measurement

Initial measurement of the roughened substrate is necessary to estimate the thickness of the coating after deposition. A micrometer is typically used. **Note**: Grit blasting the surface may add 1 to 4 mils (0.001 to 0.004 inches) of thickness to the sample measurement. It is highly recommended to measure thicknesses after grit blasting.

i Manual Micrometers

The manual micrometer is a U-shaped device with a threaded spindle on one end, and a small anvil on the other. The operator turns the spindle to advance its end towards the anvil on the opposite site. The micrometer closes on the sample. Do not over tighten the spindle on the sample. ***Stop when the spindle touches the sample and cannot turn further***. To ensure the greatest precision, many manual micrometers will be equipped with a ratchet and stop lock that stops the advance of the spindle after a certain amount of pressure. This prevents the operator from excessively forcing the spindle. Typical manual micrometers have a range of one inch. Different micrometers are needed to measure sizes between 0 and 1 inches, 1 and 2 inches, etc. **Figure** 4 shows a picture of a manual micrometer used to measure up to 1 inch.

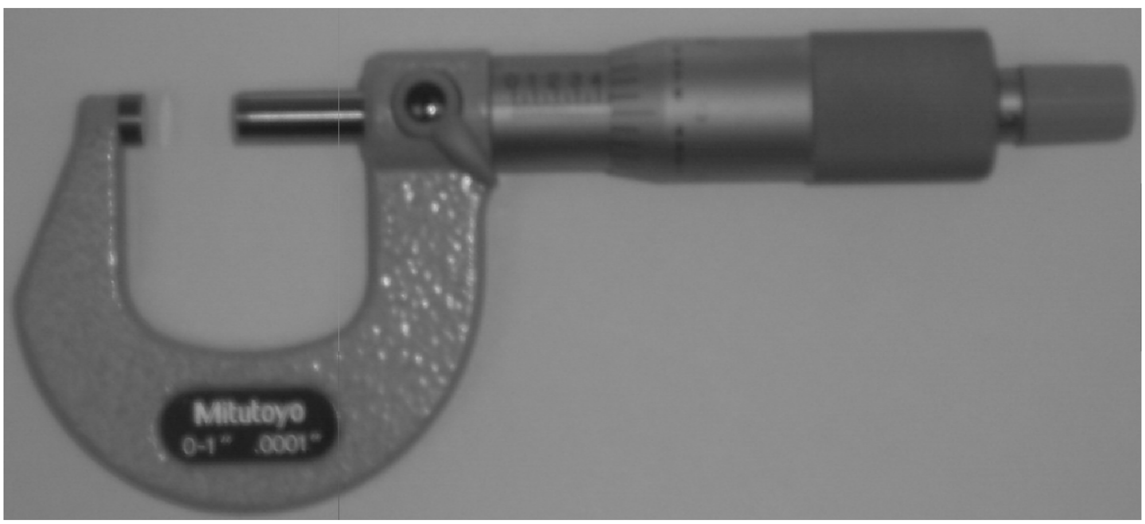


Figure 4 A typical manual micrometer

Manual micrometers come complete with a vernier scale to provide greater sensitivity to 0.0001 inches (2.54 microns). **Figure 5** shows an exploded view of a vernier scale.

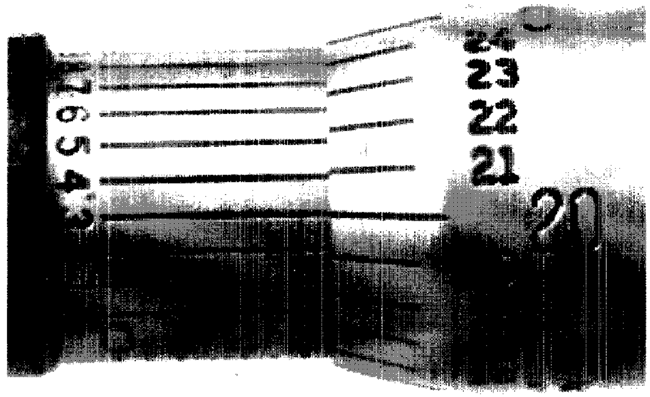


Figure 5 Exploded view of a vernier scale

A vernier scale consists of two series of lines that are positioned next to one another. The lines in one set are spaced slightly closer together (on a stationary sleeve) than the lines on the other set (on a rotating thimble). The operator examines the scale to see which pair lines up with each other. The more closely spaced lines on the stationary sleeve each have a matching number. These numbers equip the device with more accurate measurement capability, i.e., an additional decimal place in measurement values.

ii Reading a Manual Micrometer

When using a micrometer to measure a sample, it is important to note that the spindle has markings along a stationary sleeve and around a revolving thimble.

Follow these steps to read a micrometer:

a) Note the last visible number along the sleeve. This indicates the value in the tenths position.
b) Note the number of completely visible divisions on the sleeve after the whole number. Each division indicates 0.025 inches after the whole number. This will give a hundredths position.
c) Note the value on the thimble that is at or below the line along the sleeve. This indicates an additional hundredths or thousandths position, depending on the value.
d) If the micrometer has a vernier scale, note the line pairing that aligns the best. This indicates the ten-thousandths position.
e) Add the values to calculate the measurement.

Figure 6 shows the procedure of calculating a measurement with the micrometer. Note the positions of the spindle, thimble, numbers, and lines.

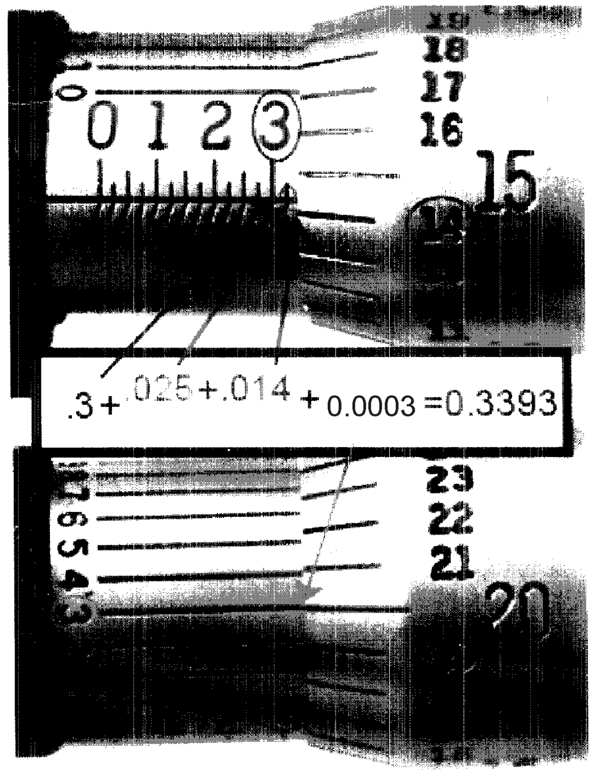


Figure 6 Reading the micrometer

4 Operator Preparation A: Program Robot

i General Information on Robot Programming for Thermal Spraying

Please consult your department manager for the training manual for your robot.

Irrespective of the type of robot used for deposition, the following rules of thumb should be employed when programming the robot and setting distances:

a) Determine the depth (width) of a single line of deposited coating. The increment for moving the robot up or down the surface of the substrate should be about **one-third** the depth of the line.

b) When programming the robot, there must be a "point of approach" that is at least 125 mm (5 inches) from the edge of the substrate. A second point, a "point of departure" must be programmed to be at least 75 mm (3 inches) from the edge of the substrate.

These two consecutive points will ensure that the torch and the jet are stable before deposition.

c) To ensure full coverage of the coated surfaces, the robot should be programmed to allow the torch to pass at least 25 mm (1 inch) above and below the substrate.
d) For thermal spraying processes, the stand-off distances are typically 50 mm (2 inches) or larger. For cold-gas dynamic spraying, that distance is about 10 mm. Stand-off distance is the distance between the torch and the substrate.
e) For thermal spraying, the robot (and torch) speed must be constant.
f) After ***full*** completion of a project, leave the robot in a predetermined home or maintenance position. This is usually specified and pre-programmed into the robot by the shop manager. It serves to leave the robot in a neutral, "ready" position for the next user.

ii Specific Information for the Motoman HP20 Robot

The following points are information specific to the programming and operation of the Motoman HP20 robot:

a) The units of length can be millimeters or micrometers.
b) The units of time are seconds.
c) The accuracy of the robot is 500 μm at full speed.
d) The maximum robot velocity is 1500 mm/s.
e) A joint movement is defined as MOVJ; Joint velocities are denoted as VJ. For thermal spraying, VJ is 10% to 25% of the maximum robot velocity.
f) The MOVL function will produce a linear motion of the object attached to the robot. "V" is the actual velocity of the robot during execution of the function.
g) Use the following procedure to set the HP20 robot in the maintenance position:
    i) Ensure that the robot is in <PLAY MODE>
    ii) Ensure that the <PLAY ENABLE MODE> button on the NX-100 controller is ON
    iii) Ensure that the SERVO button on the touch pendant is ON
    iv) On the touch pendant screen, click on the <JOB> button. This is the job key in very top left corner of the touch pendant screen.

v) Select <CALL MASTER JOB>

vi) Click the green START button at the top of the touch pendant.

This will place the robot in the Maintenance Position. When in this position, you will have enough space to pass in front of the robot to change substrates, add powder to the feeder, check on other things, etc.

g) Definition of user-defined data variables – D variables

D Variable	Definition	Comments
D000	Used for Calculations	DO NOT USE
D001	INC (µm)	Increments in µm
D002	LAYER	Number of passes
D003	VELOCITY (0.1 mm/s)	Robot velocity
D004	WIDTH (µm)	Distance: Left to right
D005	HEIGHT (µm)	Distance: Top to bottom
D006	SOD (µm)	Standoff distance

h) *Example*: Using user-defined data variables – D variables

Consider a 60 mm W by 90 mm H substrate sample for thermal spraying. Only 2 layers (2 torch passes) of coating are needed. The torch speed is 500 mm/s and the stand-off distance is 50 mm. A single line of deposited coating has a width of 6 mm. The D variables for the robot will be:

D Variable	Value	Comments
D000	Used for Calculations	DO NOT USE
D001	2,000 µm	Increments of 2 mm (1/3 of 6 mm)
D002	2	2 passes
D003	5,000 (0.1 mm/s)	5000 * 0.1 mm/s = 500 mm/s
D004	210,000 µm	75 mm + 60 mm + 75 mm
D005	140,000 µm	25 mm + 90 mm + 25 mm
D006	50,000 µm	50 mm

iii Example Program: Triangular Path

Program the HP20 robot to map the path of a triangle.

THE MAIN PROGRAM			
LINE	**POSITION#**	**COMMAND**	**COMMENTS**
0000		NOP	Start of program
0001	001	MOVJ VJ=25.00 PL=1	First point of the triangle (Point 1)
0002	002	MOVL V=370 PL=1	From point 1 to point 2 (1st side of triangle)
0003	003	MOVL V=370 PL=1	From point 2 to point 3 (2nd side of triangle)
0004	004	MOVL V=370 PL=1	Back to the first point (3rd side of triangle)
0005		END	End program

iv Example Program: Trapezoidal Path

Program the HP20 robot to map the path of a trapezoid.

THE MAIN PROGRAM			
LINE	**POSITION#**	**COMMAND**	**COMMENTS**
0000		NOP	Start of program
0001	001	MOVJ VJ=25.00 PL=1	First point of the trapezoid (Point 1)
0002	002	MOVL V=370 PL=1	From point 1 to point 2 (1st side of trapezoid)
0003	003	MOVL V=370 PL=1	From point 2 to point 3 (2nd side of trapezoid)
0004	004	MOVL V=370 PL=1	From point 3 to point 4 (3rd side of trapezoid)
0005	005	MOVL V=370 PL=1	Back to the first point (4th side of trapezoid)
0006		END	End program

v Example Program: Trapezoidal Path with Multiple Passes

Program the HP20 robot to map the path of a trapezoid with n number of passes or loops.

THE MAIN PROGRAM			
LINE	**POSITION#**	**COMMAND**	**COMMENTS**
0000		NOP	Start of program
0001	001	MOVJ VJ=25.00 PL=1	Toward the first point of the trapezoid
0002		SET I001 D002	Number of passes will be selected in D002 variable and placed in I001
0003		*LAYER	Label defined for number of passes
0004		DEC I001	Subtract 1 from the value assigned to I001 through D002
0005	002	MOVL V=370 PL=1	From point 1 to point 2 (1st side of trapezoid)
0006	003	MOVL V=370 PL=1	From point 2 to point 3 (2nd side of trapezoid)
0007	004	MOVL V=370 PL=1	From point 3 to point 4 (3rd side of trapezoid)
0008	005	MOVL V=370 PL=1	Back to the first point (4th side of trapezoid)
0009		JUMP *LAYER IF I001>0	Repeat lines 0005 to 0008 if I001>0 after decrement by 1
0010		END	End program

vi Example Program: 10-Layered Coating Deposition with Wait Times 1

Deposit a 10-layered thermal-sprayed coating on a rectangular strip that is 130 mm W by 10 mm H. It was found that the width of 1 line of the deposited coating was 10 mm. The process requires a wait time of 30 seconds after every 2 passes of the torch to avoid overheating the substrate. Program the HP20 robot to do this task.

THE MAIN PROGRAM			
LINE	**POSITION #**	**COMMAND**	**COMMENTS**
0000		NOP	Start of program
0001	001	MOVJ VJ = 25.00 PL = 1	Point of approach - 125 mm from edge of substrate
0002		SET I001 D002	Set an integer to the D002 variable. D002 = 5 for 10 passes
0003		*LAYER	Label definition for # of passes
0004		DEC I001	DEC - Subtract 1 from the value assigned to I001 through D002
0005		SET I010 0	For timing: Set an integer to start at 0
0006		INC I010	INC – Increase I010 value by 1
0007	002	MOVL V = 370.0 PL = 1	Point of departure - 75 mm from edge of substrate
0008	003	MOVL V = 370.0 PL = 1	Point located 75 mm from other edge of substrate – 1st Pass
0009	004	MOVL V = 370.0 PL = 1	Point of departure - 75 mm from edge of substrate – 2nd Pass
0010		CALL JOB: TIMER IF I010 = 2	Call the TIMER program to wait 30 seconds after 2nd Pass
0011		JUMP *LAYER IF I001 > 0	Repeat Lines 0007 to 0009 if I001 > 0 after decrease by 1
0012	005	MOVL V = 370.0 PL = 1	Return to point of departure
0013	006	MOVJ VJ = 25.00 PL = 1	Return to point of approach
0014		END	End program
THE TIMER PROGRAM			
0000		NOP	Start of program
0002		TIMER T = 30	30 seconds wait time
0003		END	End program

Note: PL = Positioning Level. Typically, PL = 1 for thermal spraying

vii Example Program: *n*-Layered Coating Deposition with Wait Times 2

Deposit an n-layered thermal-sprayed coating on a rectangular strip. Program a specified wait time after 2 passes to preheat the substrate. Follow with multiple non-stop passes.

THE MAIN PROGRAM			
LINE	**POSITION#**	**COMMAND**	**COMMENTS**
0000		NOP	Start of program
0001	001	MOVJ VJ=25.00 PL=1	Point of approach - 125 mm from edge of substrate
0002		SET I001 D002	Set an integer to the D002 variable.
0003		*LAYER	Label defined for number of passes
0004		DEC I001	Subtract 1 from the value assigned to I001 through D002
0005	002	MOVL V=370 PL=1	Point of departure - 75 mm from edge of substrate
0006	003	MOVL V=370 PL=1	Point located 75 mm from other edge of substrate
0007	004	MOVL V=370 PL=1	Point of departure - 75 mm from edge of substrate
0008		JUMP *WAIT IF I001=4	Jumps to line 0010 for the wait function after 2 passes
0009		JUMP *NOWAIT	Skips the wait function if I001≠4 and jumps to line 0012
0010		*WAIT	Label definition for wait function
0011		WAIT IN#(1)=ON T=5	The program waits for 5 seconds
0012		*NOWAIT	Label definition for skipping the wait function
0013		JUMP *LAYER IF I001>0	Repeat lines 0005 to 0007 if I001>0 after decreased by 1
0014	005	MOVL V=370 PL=1	Return to point of departure
0015	006	MOVL V=370 PL=1	Return to point of approach
0016		END	End program

5 Operator Preparation B: Identify Torch Spray Parameters

The deposition of the powders to fabricate the coating will require specific spray parameters. In addition, each type of thermal spray process will require different spray parameters. For the purposes of this training module, only the air plasma spray process will be considered. Other spray processes such as flame spraying, high velocity oxy-fuel (HVOF) spraying, and cold spraying require similar types of parameters. The major air plasma spray parameters are identified below.

i Spray Parameters – Air Plasma Spraying

a) **Plasma gases**: These are used to generate the plasma jet. Their flow rates are needed.

Primary gas: Typically, argon or nitrogen

Secondary gases: Typically, helium and/or hydrogen. (**Note**: Use of hydrogen, in addition to helium will increase the heat transfer to the powder particles)

b) **Plasma torch power**

For most plasma spray systems (e.g. 9MC plasma spray controller system), the voltage or the current must be modulated to achieve the appropriate power. In addition to modulating the voltage or the current, the flow rate of the plasma gases must also be modulated. For example, the operator may set the plasma gas flow rates constant and modulate the voltage input to the torch. The controller, in turn, will report the input current and power.

c) **Torch velocity**

Velocity of the torch may be programmed through the controller. It is usually reported in inches per second (IPS) or inches per minute (IPM). Slower velocities will produce thicker coatings per pass. Typically, the torch velocity is approximately 800 to 1200 IPM (340 mm/s to 510 mm/s).

d) **Stand-off distance**

Stand-off distance is the distance between the torch and the substrate. An appropriate stand-off distance will ensure that the powder particles are fully molten before deposition, and that the substrate does not overheat during spraying.

e) **Powder Feed Rate**

Select an appropriate powder feed rate to avoid clogging of the powder tubes and to ensure that most particles are fully melted by the plasma jet. The powder feed rate is usually controlled by modulating the powder carrier gas flow rate. Powder feed rates can range between 10 to 15 lbm/h. Typically, the carrier gas is air. However, nitrogen may be used. It is very important to conduct leak checks on the powder dispenser. This will ensure that the selected powder parameters are correct, as shown on the display.

Specific values of these parameters will depend on the type of powder that will be deposited and the required quality of the final coating. These parameters are determined after experimentation, consultation with research laboratories or thermal spraying job shops, and/or from the powder manufacturers and suppliers.

It is the responsibility of the operator/researcher to enter all the appropriate parameters into the appropriate spray parameter file. **Figure 7** shows examples of spray parameter files for cold spraying and air plasma spraying.

GDS COLD SPRAY						
Date of Creation	Date of Modification		User			
March 10, 2009	March 10, 2009		David Poyaoan/André McDonald			
Powder						
Powder Blend Composition	WC	Al	Fe			
Volume Percentage	35%	30%	35%			
Powder Size Distribution	WC (-45+20 microns); Al (-90+63 microns); Fe (-63+45 microns)					
Powder Supplier and Number	Sulzer Metco: WC (WC-12Co); Al (54NS-1); Fe (4052)					
Powder Feed Rate	30%					
Air						
Air Pressure	100 psi	Air Temperature	350 deg C			
Substrate						
Material	Low carbon steel					
Supplier and Part Number	McMaster-Carr					
Substrate Temperature	24 deg C					
Substrate Roughness						
Robot and Torch						
Stand-off Distance	3 cm					
Torch Speed	400 mm/s					
Client Information						
Client Name	N/A					
Project Title	Cold-sprayed WC-MMC					
Comments	Spraying was done by Centerline, Inc. in Windsor, ON. Powder preparation by David Poyaoan at the U of Alberta					

3MBM PLASMA SPRAY TORCH					
Date of Creation		Date of Modification		User	
April 6, 2008		May 25, 2009		Navid Pourjavad	
Powder					
Powder		TiO2 (conventional)			
Volume Percentage		100%			
Powder Size Distribution		TiO2 (-63+20 microns)			
Powder Supplier and Number		Sulzer Metco 102			
Carrier Air Flow Rate (SCFH)		15			
Powder Feed Rate		12 lb/h			
Plasma Parameters					
Voltage (V)	420	Current (A)	84	Power (kW)	35.3
Argon Flow Rate	35 Lpm	Helium Flow Rate	24 Lpm	Gas Flow Rate	
Nitrogen Flow Rate		Hydrogen Flow Rate		Gas Flow Rate	
Substrate					
Material	Low carbon steel				
Supplier and Part Number		McMaster-Carr 8910K116			
Substrate Temperature		200 deg C			
Substrate Roughness		4.3 microns			
Robot and Torch					
Stand-off Distance		100 cm			
Torch Speed		480 mm/s			
Client Information					
Client Name		BMW Canada			
Project Title		Titania Coatings for Lustrous Finish			
Comments		Non-Research project. Service for fee.			

Figure 7 Examples of spray parameter files for cold spraying and air plasma spraying

6 Spraying

a) Start the dust collector system.

b) Initiate the robot. This step assumes that the robot has been programmed and verified.

c) Start the torch system. Enter the selected flow rates of the plasma gases and voltage/current. Select the appropriate stand-off distance. Do this step with the torch away from the substrate (to the side).

d) If required, start the turntable system.

e) Pass the torch, without powder, over the substrate. The high speed of the high temperature jet will remove residual grit from the substrate surface.

f) Move the torch away from the substrate (e.g. to the side). Open the powder feed system. Do a visual verification of the presence of powder particles within the plasma jet.

g) Start the torch passes. As mentioned above in Section 3, the robot may be programmed to complete all the required passes. The passes may also be controlled by the operator at the controller.

h) Typically, 0.5 to 2 mils (0.0005 to 0.002 inches) thick layers are deposited per pass.

i) A pyrometer can be used to monitor the coating temperature during spraying. Coating temperatures should be maintained on the order of 140 to 160^{o}C. For metals, in particular, this will ensure that oxidation is kept at a minimum. Oxidation reduces the overall quality of the coatings. It is suggested to adhere to these temperature limits for ceramics. If needed, the surface temperature of ceramic coatings may be increased.

7 Coating Thickness Measurement

Measurement of the thickness of the coating-substrate ensemble is done with a micrometer. The difference between the combined thickness and the thickness of the bare substrate will give the coating thickness.

For the thermal spraying of as-sprayed (unpolished) coatings, the thickness can be accurate to within 1 to 2 mils (0.001 to 0.002 inches). As-sprayed coatings are usually about 10 to 20 mils (0.010 to 0.020 inches) thicker than the finished, grinded, and polished coating. The thicker coating will provide the grinder/polisher with material for polishing to the final, required thickness.

III Safety Considerations

1 General Considerations

The thermal spray process is a high temperature, high velocity deposition process. As a result, every operator must be aware of and adhere to strict safety issues. Here are a few important safety points:

a) Wear safety goggles at all times during spraying.
b) Noise levels during thermal spraying may be on the order of 120 dBA and higher. Operators will typically work about 10 feet from the torches, which will reduce the noise levels to about 110 dBA. An acoustical room will reduce the noise level to about 90 dBA. Normal noise levels should not exceed 85 dBA. Therefore, ear muffs ***should*** be worn if exposure is expected to exceed 2 hours per day.
c) Welder's gloves may be needed when handling the hot torches and substrates after deposition of the coatings.
d) Gas/respirator masks must be worn if the thermal spray processes are conducted outside an enclosed acoustical booth, and the operator is in direct contact with the processes.
e) Steel toe boots are strongly recommended.

2 Robot Safety

Safe operation of the robot is paramount in the thermal spraying process. Improper use of the robot or failure to adhere to established safety guidelines could result in serious injury, damage to equipment, or death. This training program will include robot operation safety. The trainee should consult the department manager for information or clarification of points that are unclear.

The following is a brief list of safety rules that ***must*** always be followed during programming and operation of the robot.

a) Do not enter the acoustical room if the robot is in the PLAY mode. Put the robot in TEACH mode before entering the room.
b) Remain at a safe distance from the robot when testing a program in the TEACH mode. The touch pendant should be in hand.

c) Avoid the ***pinch points*** of the robot. A pinch point is an area between the robot and rigid surface where a person's body or extremity (arm, leg, etc.) could be lodged without the ability for easy removal.

IV Appendix – Standard Operating Procedures (SOP)

1 Cold Gas Dynamic Spraying: Start-up

i) Turn on the dust collector system.

* Turn BLOWER MODE to MAN

* Turn CLEANING MODE to CONT

ii) Turn on the FS Curtis SE10 air compressor.

iii) Turn on the FS Curtis air dryer.

* Air should be compressed to 130 – 150 psig.

iv) Add powder to the GDS cold spray hopper.

v) Open the "Compressed Air Ball Valve" located on the side of the acoustical booth

* The GDS cold spray unit will start (lights will appear)

vi) Power on the GDS cold spray unit.

vii) Start the GDS cold spray unit from the touch-pad console.

viii) Acknowledge the type of torch (usually set in automatic, machine-mounted mode)

ix) Specify the spray parameters by making a spray recipe.

x) At this point, and with the main door to the shop firmly closed, verify that the pressure difference in the shop is -5 to -0.20 in. of water gage during full operation of the dust collector and air handling unit.

xi) Start the torch from the GDS cold spray touch-pad console. Test the spray parameters with the robot in the "maintenance position" before running the taught program.

2 Cold Gas Dynamic Spraying: Shut-down

i) After deposition, position the robot in the "maintenance position".

ii) Stop the torch from the GDS cold spray touch-pad console.

iii) End the program and close the GDS cold spray system from the touch-pad console.

iv) Turn off the GDS cold spray system.

v) Close the "Compressed Air Ball Valve" located on the side of the acoustical booth.

* The GDS cold spray unit will stop (lights will disappear)

vi) Turn off the FS Curtis SE10 air compressor.

vii) Turn off the FS Curtis air dryer.

viii) Remove the powder from the GDS cold spray hopper.

ix) Turn off the dust collector system.

* Turn CLEANING MODE to OFF
* Turn BLOWER MODE to OFF

3 Flame Spraying: Start-up

i) Turn on the dust collector system.

* Turn BLOWER MODE to MAN
* Turn CLEANING MODE to CONT

ii) Turn on the air to the 9MC controller from the air control unit.

iii) Ensure that the powder feed tube is connected to the 6PII torch.

iv) Add powder to the 5MPE powder feeder.

v) Open the primary gas (argon or nitrogen) at the gas cylinder. Ensure that the pressure at the low-pressure section of the gas regulator does not exceed 400 psig.

vi) Open the secondary gas (helium or hydrogen) at the gas cylinder. Ensure that the pressure at the low-pressure section of the gas regulator does not exceed 400 psig.

vii) Turn on the 5MPE powder feeder (on back panel).

viii) Ensure that the valve on the 6PII torch is in the “OFF” position (upright)

ix) Ensure that the gas flow levels of the fuel and oxygen at the 3GF flowmeter is set to zero.

x) Open the acetylene at the gas cylinder. The low-pressure section of the regulator should read 15 psig.

xi) Open the oxygen at the gas cylinder. The low-pressure section of the regulator should read at least 35 psig.

xii) Open the valve on the 6PII torch to the fully OPEN position (completely horizontal).

xiii) Set the acetylene flow rate to 10 SCFH (low flow) on the 3GF flowmeter.

xiv) Ignite the torch.

xv) Increase the acetylene flow rate to the desired value (on the 3GF flowmeter).

xvi) Increase the oxygen flow rate to the desired value (on the 3GF flowmeter).

xvii) Open the compressed air flow to cool the torch. Vary the pressure as desired (from the air control unit). Ensure that the flame is steady and consistent.

xviii) Under the "AUTOMATIC GUN OPERATION" section at the front of the 9MC controller, switch the system from "PREHEAT" to "FEED #1". This will allow the flow of carrier gas for the powder in the 5MPE powder feeder.

xix) Turn on the powder feed switch (mounted beside the NX100 controller).

xx) Select the desired powder feed rate.

xxi) Test the spray parameters with the robot in the "maintenance position" before running the taught program.

4 Flame Spraying: Shut-down

i) After deposition, position the robot above the substrate to avoid overshoot.

ii) Turn off the powder feed switch (mounted beside the NX100 controller).

iii) First, decrease the flow rate of oxygen to zero (at the 3GF flowmeter).

iv) Decrease the flow rate of acetylene to zero (at the 3GF flowmeter).

v) Turn off the compressed air at the air control unit.

vi) Close the valves at the acetylene and oxygen cylinders.

vii) Bleed the acetylene and oxygen gas lines.

* Open the 3GF flowmeter (acetylene and oxygen) to a high flow rate

viii) Reset the 3GF flowmeter to zero for both acetylene and oxygen.

ix) Close the valve on the 6PII torch to the "OFF" position (upright).

x) Turn off the 5MPE powder feeder (back panel).

xi) Close the valves at the primary gas (argon or nitrogen) and secondary gas cylinders.

xii) Under the "AUTOMATIC GUN OPERATION" section at the front of the 9MC controller, switch the system from "FEED #1" to "PREHEAT". This will stop the flow of carrier gas to the 5MPE powder feeder.

xiii) Turn off the compressed air to the 9MC controller (at the air control unit).

xiv) Remove the powder from the 5MPE powder feeder.

xv) Turn off the dust collector system.

* Turn CLEANING MODE to OFF
* Turn BLOWER MODE to OFF

5 Air Plasma Spraying: Start-up

i) Turn on the dust collector system.

* Turn BLOWER MODE to MAN
* Turn CLEANING MODE to CONT

ii) Turn on the air to the 9MC controller from the air control unit.

iii) Ensure that the powder feed tube is connected to the 3MBM torch.

iv) Add powder to the 5MPE powder feeder.

v) Determine the primary plasma gas that will be needed. Ensure that the primary gas (argon or nitrogen) tube is connected to the primary gas connector on the back of the 9MC controller. **Note**: If nitrogen is the primary gas, the argon gas tube **must** be connected to the "SOFT START" connector on the back of the 9MC controller.

vi) Determine the secondary plasma gas that will be needed. Ensure that the secondary gas (helium or hydrogen) tube is connected to the secondary gas connector on the back of the 9MC controller.

vii) Open the primary gas (argon or nitrogen) at the gas cylinder. Ensure that the pressure at the low-pressure section of the gas regulator does not exceed 400 psig.

viii) Open the secondary gas (helium or hydrogen) at the gas cylinder. Ensure that the pressure at the low-pressure section of the gas regulator does not exceed 400 psig.

ix) Turn on the 5MPE powder feeder (on back panel).

x) Set the "ARC CURRENT" dial on the front of the 9MC controller to 25.

xi) Disengage the red "EMERGENCY STOP BUTTON" on the front of the 9MC controller.

xii) Push the "AUTOMATIC GUN OPERATION" START button to ignite the 3MBM torch.

xiii) Increase the arc current by turning the "ARC CURRENT" dial.

xiv) Increase the primary and secondary gases, as needed. Observe the changes in the voltage.

xv) Under the “AUTOMATIC GUN OPERATION” section at the front of the 9MC controller, switch the system from “PREHEAT” to “FEED #1”. This will allow the flow of carrier gas for the powder in the 5MPE powder feeder.

xvi) Turn on the powder feed switch (mounted beside the NX100 controller).

xvii) Select the desired powder feed rate.

xviii) Test the spray parameters with the robot in the “maintenance position” before running the taught program.

6 Air Plasma Spraying: Shut-down

i) After deposition, position the robot above the substrate to avoid overshoot.

ii) Turn off the powder feed switch (mounted beside the NX100 controller).

iii) Push the STOP button under the “AUTOMATIC GUN OPERATION” section to dis-ignite the 3MBM torch.

iv) Engage the red “EMERGENCY STOP BUTTON” on the front of the 9MC controller.

v) Under the “AUTOMATIC GUN OPERATION” section at the front of the 9MC controller, switch the system from “FEED #1” to “PREHEAT”. This will stop the flow of carrier gas to the 5MPE powder feeder.

vi) Turn off the compressed air at the air control unit.

vii) Turn off the 5MPE powder feeder (back panel).

viii) Close the valves at the primary gas (argon or nitrogen) and secondary gas cylinders.

ix) Remove the powder from the 5MPE powder feeder.

x) Turn off the dust collector system.

* Turn CLEANING MODE to OFF
* Turn BLOWER MODE to OFF